Laser Sources on a Heterogeneous III-V/Silicon Platform

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***Abstract*— The heterogeneous integration of III-V semiconductor lasers on a silicon waveguide platform using DVS-BCB adhesive bonding is reviewed. Both mW-level lasers and ultra-compact laser sources are discussed.**

***Index Terms*— Heterogeneous integration, silicon photonics, semiconductor laser**

I. INTRODUCTION

Silicon-based photonic integrated circuits are gaining considerable importance for a variety of applications, from telecommunications to sensors. The interest in this technology stems mostly from the expectation that the maturity and low cost of CMOS-technology can be applied for advanced photonics products. Other driving forces for silicon photonics include the design richness associated with high refractive index contrast as well as the potential for integration of photonics with electronics. Building light sources, and in particular laser sources, on integrated silicon circuits is a long sought goal, on one hand in order to complete the functionality of the integrated circuit with one or several light sources but on the other hand also as a manufacturing approach for lasers on large wafers in CMOS-fabs. In terms of device performance the most successful approach to date is definitely the hybrid (also called heterogeneous) III-V on silicon laser. In this device thin layers of III-V semiconductors are bonded to silicon. The laser cavity gets its gain from the III-V layers but couples its output light into a silicon waveguide. Often part of the cavity structure is implemented by means of patterning in silicon, thereby taking advantage of the resolution and accuracy of lithography tools in CMOS fabs. In that sense these hybrid III-V/silicon lasers take the best of two worlds. Two main technologies are used to heterogeneously integrate III-V epitaxial layer stacks on a silicon waveguide circuit: molecular bonding and adhesive bonding. In the Photonics Research Group – Ghent University / imec, we focus on adhesive die-to-wafer and wafer-to-wafer processes, based on DVS-BCB as a bonding agent, given the relaxed requirements on the III-V wafer surface quality (contamination, particles, roughness). The technology is described in detail in [1]. Based on this technology, various types of heterogeneously integrated laser sources were fabricated. Depending on the application, different laser architectures can be envisioned. For inter-chip interconnect applications for example, mW level laser sources are required (multimode or single mode), for which footprint is less of an issue. However, when considering intra-chip optical interconnect, footprint and power consumption are much more important. Therefore, different laser designs were developed that address these different requirements/applications.

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II. MILLIWATT-LEVEL HETEROGENEOUS LASER SOURCES

In order to achieve milliwatt-level laser sources on a silicon chip, a hybrid mode approach, analogous to what is used at UCSB/Intel [2], was developed. In this approach the optical mode is predominantly confined to the silicon waveguide layer. The difference between both designs is the presence of the low-index DVS-BCB bonding layer (sub 100nm) between the silicon waveguide and the III-V epitaxy. Careful design of the epitaxial layer stack is required to accommodate variations in bonding layer thickness. Simulations show that with a careful design, the influence of a DVS-BCB thickness variation of +/- 50nm, can be minimized. As a proof-of-principle, hybrid 1310nm Fabry-Perot laser diodes were realized, as shown in figure 1 [3]. 4mW laser output power from a single laser facet at room temperature was obtained. By incorporating a grating in the top surface of the silicon waveguide layer, single mode lasers can be obtained.

Since in these devices the optical mode is predominantly confined in the silicon waveguide layer, the confinement factor in the III-V quantum wells is relatively low. This impacts the threshold current of the device. Therefore, an alternative laser architecture was developed, in which the optical mode is fully confined to the III-V waveguide layer in the gain section, while the mode is pushed into the silicon waveguide layer for the (potentially wavelength selective) feedback [4]. This device structure is shown in figure 2. 2mW laser output from a cleaved Fabry-Perot device and operation up to 45C was obtained. Sub-500nm taper tips are required to obtain low reflection and high efficiency coupling from the III-V to the silicon waveguide layer.

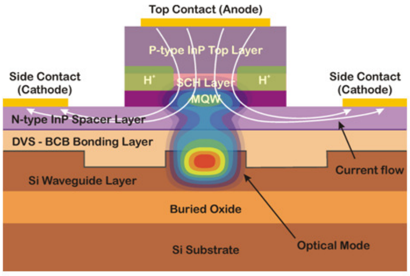

Figure 1: Hybrid laser layout

The incorporation of wavelength selective feedback elements such as arrayed waveguide gratings, ring resonators and Bragg reflectors are under way. Also the co-integration with silicon modulators is envisioned.

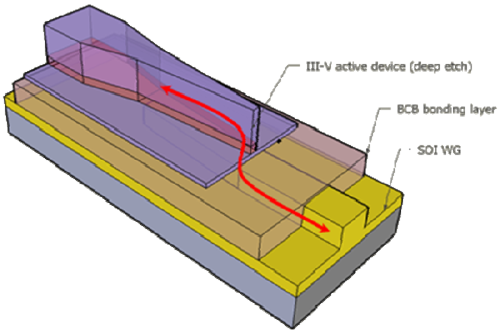

Figure 2: III-V/silicon laser with tight confinement in the III-V gain region and an adiabatic taper to couple to the silicon waveguide layer

III. Ultra-compact heterogeneous light sources

When footprint and power consumption become critical, definitely a high confinement of the optical mode in the quantum wells is required, together with a low modal volume. This is exploited both in microdisk lasers and photonic crystal lasers integrated on a silicon waveguide circuit. The microdisk laser structure is detailed in figure 3 [1]. The 7.5µm diameter disk supports whispering gallery modes, allowing for straight-forward electrical injection using a central contact. A tunnel junction is used to prevent excessive losses of the optical mode due to p-type doping. The devices show a threshold below 0.5mA and an output power (coupled to the silicon waveguide circuit) of over 100µW. Recently, the fabrication of these devices on a 200mm wafer in a CMOS pilot line was demonstrated.

A further reduction in modal volume (and hence threshold) could be achieved using III-V photonic crystal lasers heterogeneously integrated on a silicon waveguide circuit. Devices as shown in figure 4, consisting of a III-V photonic wire in which a 1D photonic crystal cavity is defined, on top of a silicon waveguide, were realized [5].

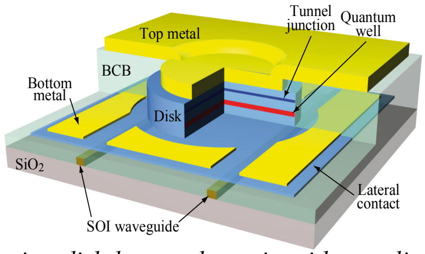

Figure 3:microdisk laser schematic with coupling to silicon waveguides

Laser emission and coupling of light to the silicon waveguide circuit was achieved, by optically pumping the device, both from the top or from the silicon waveguide layer, using a near-infrared pump beam.

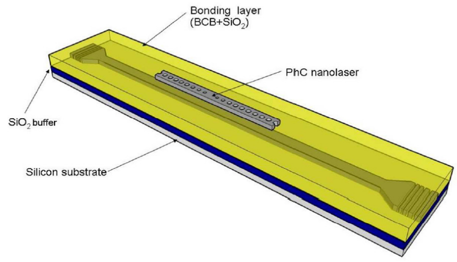

Figure 4: Schematic of the fabricated photonic crystal laser

IV. Conclusion

The combination of high precision patterning methods in silicon fabs and high gain provided by III-V semiconductors provides a winning combination for advanced lasers. The design space is large and there is ample opportunity for optimization towards specific performance objectives (power, spectral properties, pulsed operation, size, etc.). The critical technological step in hybrid III-V / silicon lasers is obviously the die-to-wafer bonding step. While early approaches suffered from low yield the technology has now become more mature.

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